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A range of combined error correction and recording channel code schemes

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Summary

This report describes an error correction scheme which uses the inherent error detection capability of a channel code as one dimension of the correction process. This reduces the total overheads in terms of hardware and data rate required for correction, allowing the advantages of a channel code whilst minimising the overheads.

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1. Introduction

To enable digital techniques to be fully adopted in television studios an essential requirement is a digital video tape recorder (DVTR). This would still employ magnetic tape as the recording medium, but the signals would be impressed upon it in digital form. Such a machine would have to provide all the operational facilities of existing analogue machines and produce an output of at least the same quality.

An important consideration in the design of a DVTR is channel coding and error strategy. Channel coding is necessary to ensure that the input bit pattern alternates sufficiently frequently to maintain a change of flux in the record head - a continuous stream of 1's or O's would cause loss of record head output. Error detection and correction are necessary to compensate for bit errors caused by noise, tape imperfections and dirt.

Conventionally, channel coding and error protection are treated independently of one another resulting in various compromises between tolerance to errors, the preconditions put upon picture content, and data overheads.

Channel coding usually entails adding redundancy to the incoming binary data so that only preferred digit patterns are recorded. This redundancy gives a certain error detection capability which may be used in the correction process.

The Report describes a range of schemes in which this and some additional data are used for error protection, so as to minimise overheads both in terms of hardware and data rate.

Although developed for use with digital magnetic recording this scheme could also be applicable to serial data transmission systems.

Fig. 1 is a schematic diagram of the relevant parts of a DVTR employing channel coding and error protection techniques. It shows the main blocks concerned with the error and channel coding and decoding processes which are described in more detail in Section 5.

2. Errors in recording

When recording digital information on tape, brief tests have indicated that there are predominantly two types of error pattern.

The first type is single-bit errors induced by noise entering the channel. The spectrum of this noise is normally high frequency emphasised (blue noise) because it is affected directly by replay equalisation. These single-bit errors, however, normally comprise only a small fraction of the total error incidence for two reasons. Firstly, in magnetic recording the amplitude of the replayed signal diminishes rapidly with increasing frequency near the upper limit; a small reduction in packing density can therefore yield a significant increase in signal-to-noise ratio and therefore a lowering of error rate. Secondly, near the

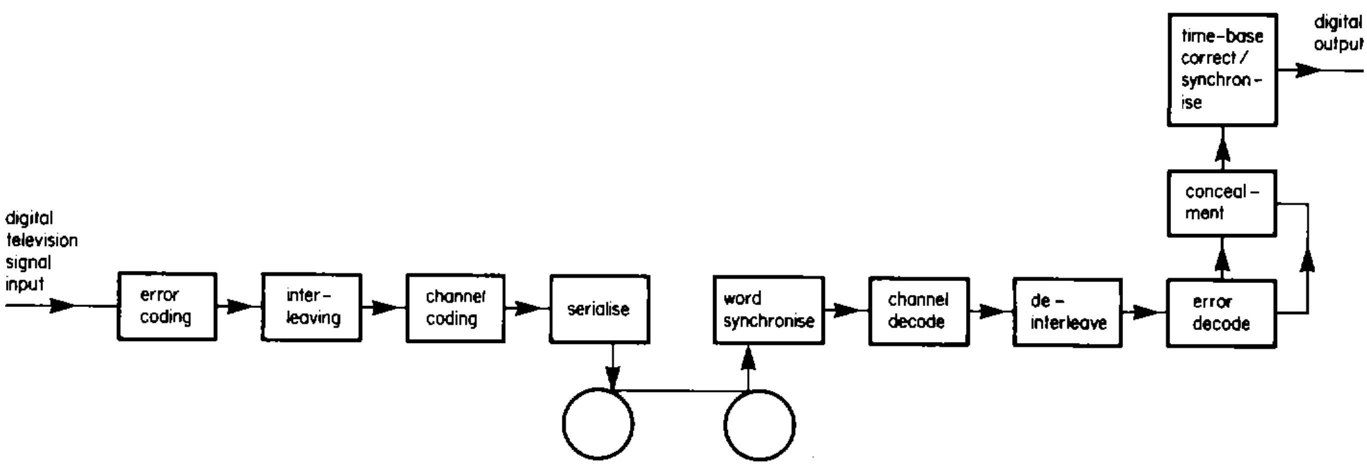

Fig. 1 – Schematic of typical Digital Video Tape Recorder.

upper frequency limit of the recorder, the signal amplitude off tape is prone to fluctuate. A reasonable headroom to allow for the troughs of these fluctuations ensures the channel is operating under low noise conditions for the majority of the time.

The second type comprises burst errors. These result from reductions in output from the replay head caused either by tape imperfections and scratches, or by dust particles getting between the head and the tape. Clearly the number of bits affected depends on the packing density and the dropout size.

2.1. Noise-induced errors

If the noise spectrum is white (or blue) up to a frequency equal to half the bit rate, then each bit will have a statistically independent probability of error equal to the bit error ratio, i.e., the number of erroneous bits divided by the total number of bits. Fig. 2 shows the probability of burst errors of between 1 and 9 bits for various bit error ratios.

The majority of noise-induced errors can be seen to be single-bit. As error ratios increase, however, the likelihood of having several independent errors within a particular block of data increases. This will determine the failure

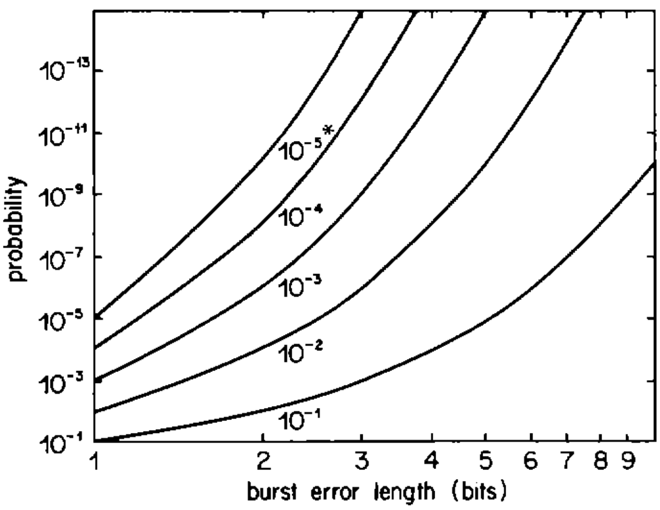

Fig. 2 — Probability of different burst error lengths for various bit error ratios of random noise-induced errors.

* lines of constant bit error ratio.

rate of a particular error correction code for this type of error. Fig. 3 shows the probability of experiencing various numbers of errors in a 20-bit constraint for various error ratios. Again for low

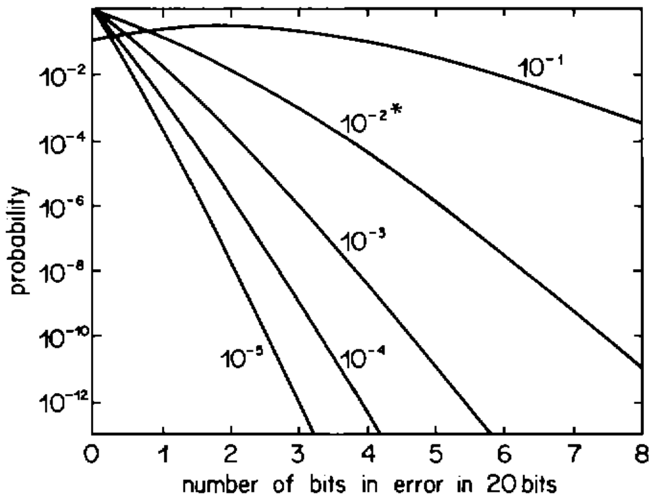

Fig. 3 — Probability of number of bits in error in a 20-bit constraint for various bit error ratios of random noise-induced errors.

* lines of constant bit error ratio.

error ratios single error events are by far the most probable. For very high error ratios, however, two errors become more likely than one.

2.2. Dropout-induced errors

Experiments with various tape transports, including longitudinal digital machines, helical scan analogue and helical digital recorders suggest a similar size for the majority of dropouts of about 100 μm to 1000 μm (0.004 inches to 0.04 inches). This results in typical dropout lengths of from 100 bits to about 2500 bits for linear packing densities of from 25,000 to 60,000 bits per inch.

From this we can plot the probability of different burst error lengths that would be expected from a magnetic tape transport. This is shown in Fig. 4.

3. Channel coding

The aim of channel coding is to convert input non-return to zero (NRZ) data into a form that can readily be recorded and replayed from tape. It is difficult to recover d.c. information with conventional tape-heads and so it is desirable to code a sequence of input bits into a sequence of coded bits which possess a nearly equal number of binary 1's and 0's. Frequent data transitions must occur in the coded domain to allow also for accurate resampling of the recovered data. This necessarily involves the spreading of information from one data bit to several coded bits and has the

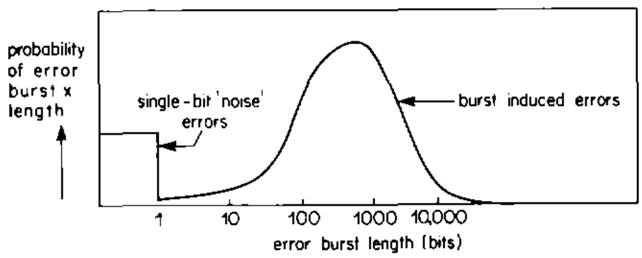

Fig. 4 – Likely error distribution for magnetic tape recording.

detrimental effect of extending error lengths in the decoded data. In particular, single-bit errors which are relatively easy to detect and correct are converted into short burst errors. This is significant since the error correction stage is usually positioned before the channel coding stage in a complete recording system. In magnetic recording, however, this extension does not significantly increase error ratios because most errors result from long dropouts.

4. Correcting errors

4.1. General

Error correction codes may usually be specified by their ability to correct a certain number of errors within a certain constraint length and also by their overhead or redundancy. The errors may be single-bit or burst errors. For instance, a simple Hamming[1] code can correct one bit in a constraint length of $(2^n - 1)$ with a redundancy of n bits; a Wyner Ash[1] code one bit in a length of $(n + 1)2^n$ with a redundancy of $(n + 1)$ bits.

Other codes are word based. For instance, a Reed Solomon[2] code may correct t, m-bit words in a constraint length of $(2^m - 1)$ words with a redundancy of 2t words. It is worth noting that this type of code can correct a higher proportion of the data than a single-bit correcting code for the same overhead. This results from the constraints put on the locations of the bits in error within the block. Interleaving single-bit error correcting codes to obtain a good burst performance is therefore inefficient.

It follows from Section 2 that there are predominantly two forms of error pattern in the data replayed from tape. Firstly, there are short burst errors equal to the error extension of the channel code, caused by noise. Secondly, there are long burst errors normally greater than 50-100 bits in length. Single-bit correcting codes are therefore unsuitable in most applications, word orientated codes providing a more efficient solution, particularly if the word length equals the error extension of the channel code.

In dealing with long burst errors, the conventional approach is to re-distribute them using interleaving techniques so that single-bit or short burst length error correcting codes may be used. This involves reordering the data such that a long continuous block of errors off tape effects only the correctable number of bits within a constraint length, as seen by the error decoder. Here too, word orientated codes provide a more efficient solution, enabling data to be handled in complete words, rather than bitwise, thus reducing the number of interleaving operations and considerably reducing instrumental complexity. Since word based codes are also capable of correcting a higher proportion of the data for a given overhead, they allow either a shorter interleaving block length, a lower percentage overhead or longer dropouts to be corrected.

4.2. Error detection capabilities of channel codes

It is usual to apply some form of channel coding to the input data prior to recording or serial transmission. Where redundancy is added to the data stream for this purpose, error detection is available because not all digit combinations need be used for codewords. During a period of severe data corruption, the proportion of digit errors that may be detected is simply dependent on the proportion of the total number of values, for a given codeword length, which are used in the codeset. Thus for a binary system, in which 'd' bit data words are coded into 'c' bit codewords, the proportion of errors detected is:

$$\frac{2^c - 2^d}{2_c}$$

The codeset of 2^c codewords may be organised in such a way that higher proportions of some error combinations are detected.

Taking the 20:16 code [3,4] as an example, it is capable of detecting all single-bit errors (because codewords have parity of 1's and O's) and fails to detect 1/16 of random error patterns. Whilst single-bit errors are well protected the burst performance is inadequate. Where long dropouts occur, the probability of detecting words affected can be increased by taking account of errors in adjacent words.

Suppose each decoded word, replayed from tape or recovered from a transmission link, has associated with it a notional error flag. Suppose also that if one word is detected as being in error, the flags associated with that word and those words up to s distant from the word in error were set to the error state. Then, for a long burst error, this would reduce the failure ratio to $(1/16)^s$. Thus for a five-word block the proportion missed would be $1/10^6$. For shorter dropouts the probability of detection will fall. This is shown in Fig. 5.

5. An error correction scheme

A simple error correction scheme could be devised using the inherent redundancy of the 20:16 channel code and an additional overhead, in terms of bits, of 6.25%. The additional overhead is incurred in generating a 16-bit parity word. Each bit of this word corresponds to the modulo-two sum of equivalent bits of the preceding sixteen 16-bit data words. The schematic of an error coder for deriving the parity word is shown in Fig. 6a.

The new block of seventeen words is now interleaved wordwise, i.e., scattered in time between similar words from surrounding blocks. This action ensures that no data or parity word is within a likely maximum dropout length of any other word from its own block.

Channel coding to produce 20-bit words then takes place, followed by conversion to serial data form prior to recording. After the processes of channel coding, recording, replaying and decoding the original data is recovered.

At the replay end the 20-bit interleaved words are decoded to 16-bits and any word found to contain an error, in violation of the 20:16 code, is flagged by the addition of a four-bit code. Additionally, words up to a distance of fifteen on either side of the word containing the error are also flagged, but the flags are weighted to indicate their error distance from the word in error.

When the data words are de-interleaved and reassembled into 17-word parity blocks, the words containing an error are distributed among several such blocks with the likelihood that only one word containing an error would be found in any one block. When a word containing an error is detected and flagged a new parity word is then compared with the original parity word and the comparison indicates which bits of the flagged word are in error, enabling them to be corrected. This technique enables single-word errors to be corrected, and the schematic diagram of an error decoder operating in this way is also shown in Fig. 6a. A pictorial representation of the coding and decoding process is shown in Fig. 6b; for simplicity, interleaving is omitted.

If two error distance flags of the same value are located within the same parity block, then neither can be corrected. If concealment was available as a later process the two words could simply retain the error flag as a means of identification. If the mean error rate of the system was low and the value of the flagged error distance high, i.e., close to 15, it may be desirable to leave the words uncorrected and unconcealed since the chance of them being wrong could be as small as $(1/16)^{15}$, which may be smaller than the output error ratio of the channel. Similarly, if there are two error distance flags in a block, one of which is much higher than the other it may be better to ignore the higher and correct the other word. For example, in a system prone to single-bit

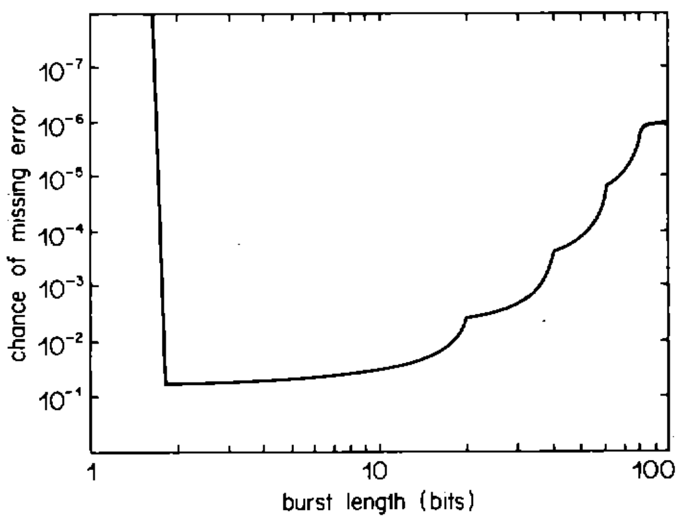

Fig. 5 — Chance of NOT detecting a burst error using the 20:16 code versus burst length, for a flagged distance of five words.

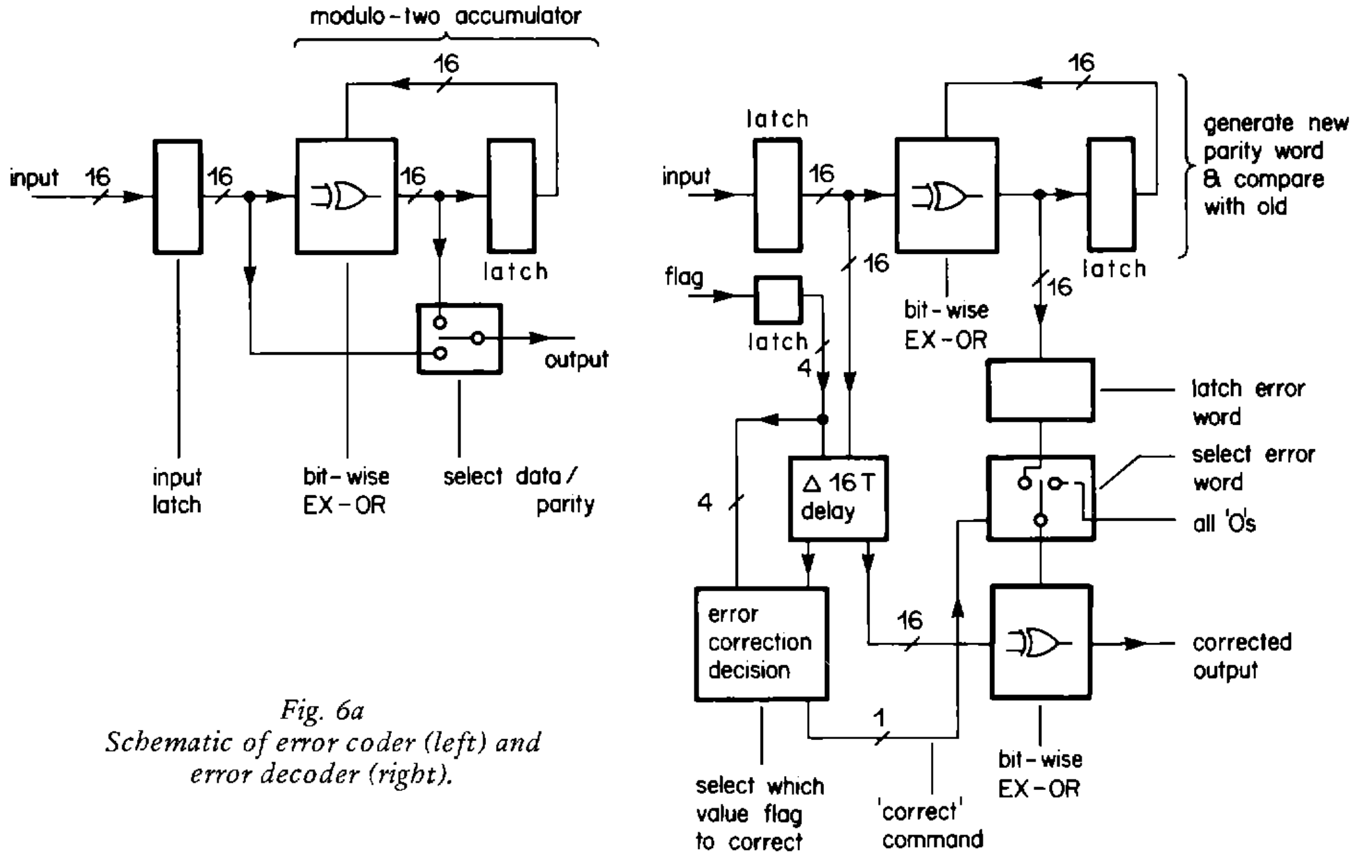

Fig. 6a
Schematic of error coder (left) and error decoder (right).

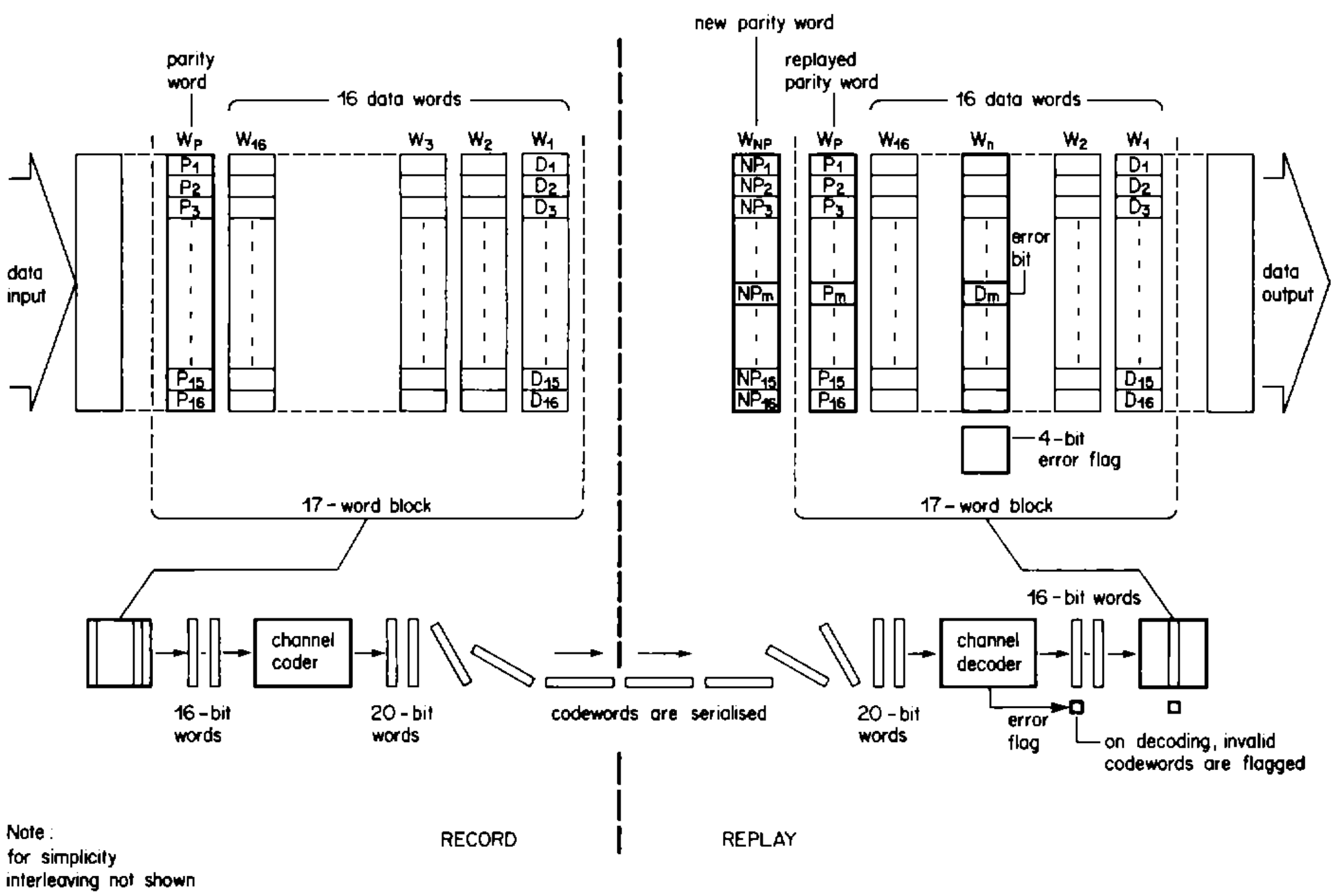

Fig. 6b — Diagram illustrating the coding and decoding process.

errors it would be absurd to try to correct words surrounding the single-bit error on the assumption that they are all part of a long dropout error. Clearly an accompanying system which measured probability of dropout length and overall error ratios would assist this decision-making process.

The aim of incorporating this decision making is to make maximum use of available error correcting data. If within an error correcting block there is no word which is certainly in error, but one word has been flagged, it is sensible to use the available redundancy to check a word that has a small degree of suspicion attached to it. Similarly, in the instance of two words being flagged it would be unwise not to correct either if the chance of the less suspect being in error was less than the output error ratio of the decoder.

Fig. 7 shows the input/output performance of the simple error correction scheme

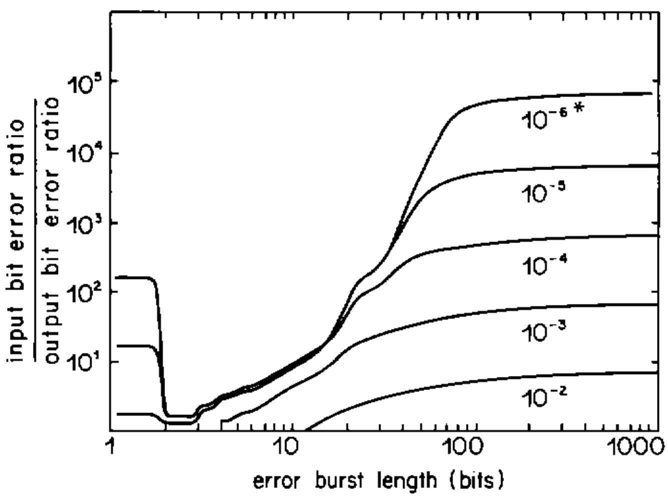

Fig. 7 — Error rate improvement for a simple 1 in 16 interleaved parity scheme using the 20:16 code for detection versus burst length, for different input error ratios.

* lines of constant input bit error ratio.

for different error burst lengths and input error ratios. It will be seen that there is an effective improvement for single-bit errors and burst errors of greater than 100 bits, which closely matches the error distribution characteristic of the channel (see Fig. 4). For comparison, the performance of a conventional scheme is shown in Fig. 8. This employs a shortened Wyner Ash code with a 12.5% overhead as used earlier by BBC Research Department in an experimental DVTR[4]. It was assumed to be working in a complete channel incorporating a 20:16 coder and decoder. In this

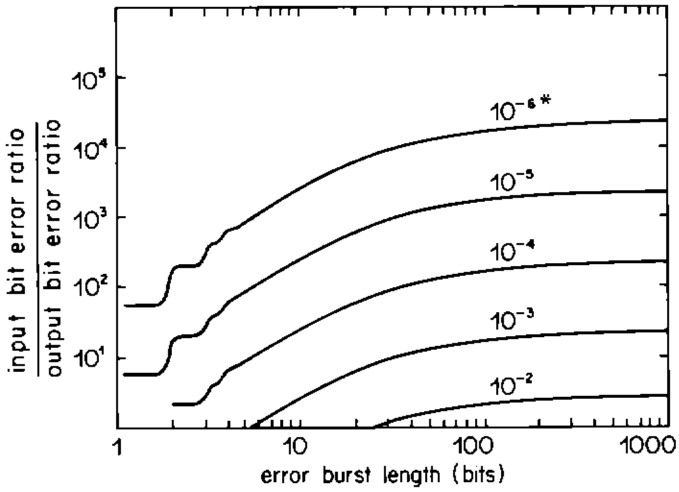

Fig. 8 — Error rate improvement for a 1 in 8 overhead shortened Wyner Ash code in a channel using the 20:16 code versus burst length, for different input error ratios.

* lines of constant input bit error ratio.

case, no use was made of the error detection capability of the channel code.

The effectiveness of the simple scheme described above relies on the assumption that few errors occur in the range 2 - 50 bits (see Section 2). Such errors could be better catered for by a three-dimensional scheme devised by creating a second parity word for every 16-word block, which also applies to data in other blocks. This scheme, which incurs a 12.5% overhead, would enable one unflagged word and two flagged words per block to be corrected. The improved performance of this code is shown in Fig. 9.

6. Error correction based on channel codes other than 20:16

Although most of the discussion in this Report has concerned the use of the 20:16 code, the same strategy could be applied to any other redundant code for which violations may be detected, e.g., 10:8[5], 8:14[6], and delay modulation[7]. For a system prone to single-bit errors, a code which guarantees parity of 1's and 0's would be important. For detecting short burst errors it is desirable that the coding block should be as long as possible. For example, although 20:16 and 10:8 have the same percentage redundancy, 10:8 can detect only 75% of short burst errors whereas 20:16 can detect 93%.

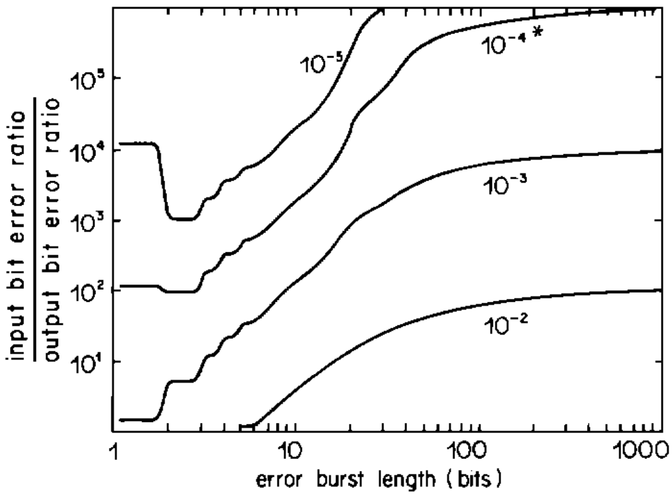

Fig. 9 — Error rate improvement for a double interleaved parity using a 1 in 8 overhead and the 20:16 code for detection versus burst length, for different input error ratios.

* lines of constant input bit error ratio.

7. Conclusions

An error correction scheme has been described which utilises the inherent error detection capability of a particular recording code, the 20:16 code. This code provides effective error detection, particularly for single-bit and long burst errors.

The scheme is based on the 20:16 code, but with added overheads which may be tailored to the user's requirements. For example, an effective amount of correction may be obtained from an additional overhead of only 6.25%. Alternatively, a high degree of correction may be achieved with an additional overhead of 12.5%.

Its performance is well matched to the probable error distribution characteristic of a DVTR record/replay channel. It is more efficient in terms of bits corrected per bit error coding overhead than any isolated error correction scheme and the instrumentation is simpler too, requiring fewer components than many other schemes.

Its effectiveness critically depends on the distribution of probabilities of error burst length, and the characteristics of the particular recorder and tape used would need to be known before an optimum scheme could be devised.

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